THERMO-MECHANICAL ANALYSIS OF ADDITIVELY MANUFACTURED HYBRID EXTRUSION DIES WITH CONFORMAL COOLING CHANNELS

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Abstract. Profile overheating and surface defects during hot aluminum extrusion can occur when seeking higher productivity rates at increased ram speed velocities. The incorporation of cooling channels in the die-design allows overcoming this process limitation by keeping the profile temperature below the melting point of the alloy used [1]. Selective laser melting (SLM) of conformal cooling channels provides, in contrast to conventional manufacturing techniques, the opportunity to place the cooling circuit inside the mandrel of a porthole-die in a well-defined position to the critical bearing region [2].

In the framework of this study, a preliminary numerical investigation on the extrusion process under the assumption of liquid nitrogen cooling is analysed. The results show, that by combining conformal cooling channels with liquid nitrogen as a cooling media high cooling rates, which are well beyond the state of the art of conventional dies, can be achieved.

In a hybrid extrusion die set-up, a part of the mandrel, that is additively manufactured, is either joined [3] or directly selective leaser melted onto the conventionally manufactured parts [4]. For a proper implementation in the extrusion process, material testing of the welded joint are needed. Thus, in the current study, tensile tests performed at room temperature for hybrid specimens, partially consisting of conventionally processed tool steel 1.2343 and partially additively manufactured 1.2709, will be presented. Moreover, four different heat treatment sequences of the hybrid specimens will be discussed. In addition, for each configuration, micro-structural images are taken to investigate failure at the bonding region. Finally, an optimal manufacturing sequence for a hybrid die with the described material combination is proposed.

1 INTRODUCTION

As for other industrial processes, the main optimization goal is to raise productivity rates by increasing ram speed. During the extrusion process, however, the temperature development in the profile needs to remain below the melting point of the alloy in use, thus, limiting the maximal possible velocity [5, 6]. Therefore, as studied amongst others by Ward et al. [1], to manage the temperature increase in the extruded profile, cooling channels for nitrogen tempering are implemented in the tool design.

During aluminum extrusion, the highest temperatures are encountered in the forming region (see Figure 1), also known as the bearing region, where the material flow reaches its final profile shape [6]. In order to efficiently position the cooling channels inside the tools as close as possible to the bearing region, conformal cooling channels manufactured by selective laser melting (SLM) are implemented in the die design, as proposed by Hölker et. al [2, 7]. The difference to channels conventionally manufactured by milling and drilling operations is that the conformal pipes can follow the contour of the of the heated surfaces and enhance a homogeneous cooling effect.

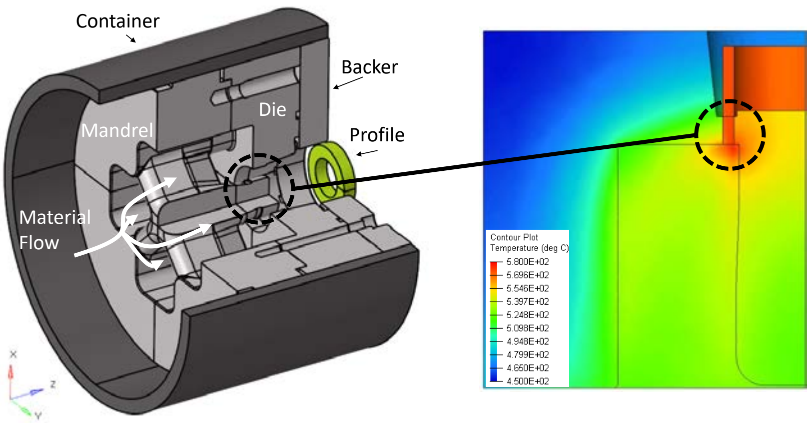


Figure 1: Exemplary critical temperature distribution of a tube profile for a four chamber porthole die

2 MANUFACTURING CONCEPTS FOR HYBRID EXTRUSION DIES

Selective laser melting of a complete extrusion tool set-up would be very cost and time intensive and also difficult to produce due for example to the restricted building chambers of the existing SLM machines, therefore, a hybrid die concept is introduced. Figure 2 pictures two possible ways of building hybrid extrusion tools. As it can be seen, to overcome the manufacturing and cost constraints, the tools can consist of both: additively and conventionally manufactured components. Moreover, the parts can either be joined or welded together. A simplified cost analysis for the production of the additively manufactured parts can be seen in Table 1. The costs are calculated under the assumption of: €$70/kg$ for the material costs and €$120/h$ for the machine costs. It is clear from this table, that to manufacture the entire mandrel by selective laser melting would not be acceptable in the industrial framework.

Table 1: Cost estimation of additive manufactured parts

	Mass *kg*	Time *h*	Material €	Machine €	Total Costs €
Insert (joined)	0.64	10	50.30	1'200	1'250.30
Insert (welded)	0.32	5	25.15	600	625.15
Mandrel (full)	16.75	262.98	1'322.86	31'557.60	32'880.46

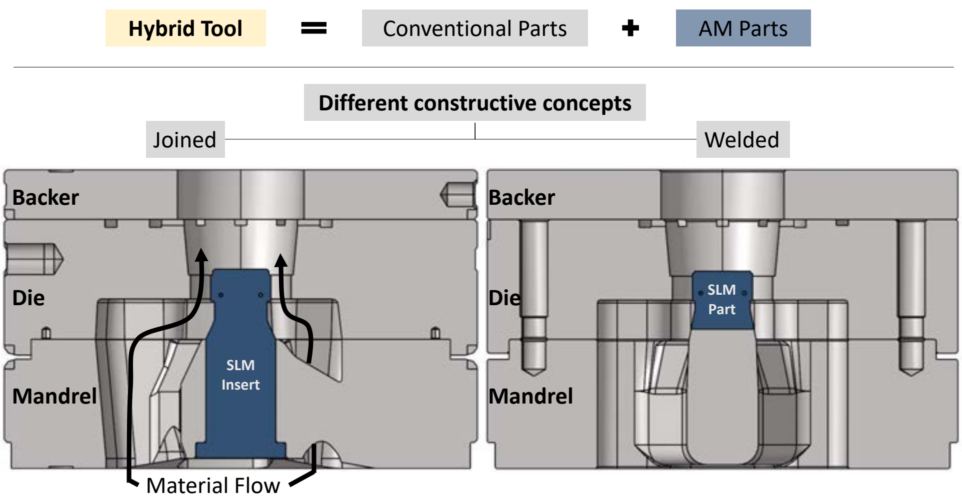


Figure 2: Design concepts for hybrid tools applied on a porthole-die for a tube profile.

There are various arguments in favor and against the hybrid constructive concepts pictured in Figure 2. The joined tool design has the advantage, that the several parts can be manufactured and heat treated separately and therefore, it has a greater flexibility regarding the material choice. However, there are more geometrical constraints because the additively manufactured insert has to fit into the mandrel and therefore, the geometrical freedom, given by the additive manufacturing technique, is more limited than in the welded tool set-up. The welded tool version, on the other hand, is more sensitive to the material selection. When the powder material for the SLM part differs from the material for the conventional part, material tests are needed to ensure the structural integrity of the insert subjected to the extrusion loads. Therefore, after a thermo-mechanical assessment of the extrusion process with and without tool cooling, introduced in Chapter 3, the results of hybrid tensile tests for the analysis of the welded tool set-up will be presented and discussed.

3 NUMERICAL INVESTIGATION OF THE EXTRUSION PROCESS

In this chapter, the results of numerical extrusion simulations are presented to show the potential and discuss the constraints of nitrogen cooling. The simulations are performed for a tube profile with a thickness of $5mm$ extruded through a five chamber porthole-die. The simulations of the extrusion process are computed with the commercial code HyperXtrude of Altair based on the ALE approach. The tools are assumed to be rigid bodies, therefore no tool deflection is computed. For the temperature dissipation into the tools a convective heat transfer coefficient of $11'000W/m^2K$ between the aluminum and the tool surfaces is defined. The workpiece material is set to a AW6060 aluminum alloy for which the Sellars-Tegart material model, implemented in HyperXtrude, is used. The model description is given by Equation 1, where n is the stress exponent, A is the reciprocal strain factor, Q is the activation energy, R is the universal gas constant, α is a constant and T is the reference temperature. The used parameter values can be seen in Table 2. These have been fitted based on material data of compression tests performed for a previous project at the institute on a dilatometer-machine.

$$\sigma = \frac{1}{\alpha} \sinh^{-1}\left(\left[\frac{Z}{A}\right]^{(1/n)} \right) \; where \; Z = \dot{\epsilon}\exp(Q/RT) \tag{1}$$

Table 2: Parameters for the Sellars-Tegart material model

n	A	Q	R	α
-	-	J/mol	$J/molK$	$1/Pa$
2.6543	1.0989e+012	209631	8.314	1.096e-007

The preliminary study is performed on the joined tool set-up pictured in Figure 2 on the left, where 1.2709 tool steel is used for the additive manufactured insert and 1.2343 tool steel is used for the conventional parts. Since only a thermal evolution is computed for the tools, the relevant material parameters for the simulations are the thermal conductivities of the two steels used. Their values are $\lambda = 20\ W/mK$ for 1.2709 and $\lambda = 28.5\ W/mK$ for 1.2343. The billet length is considered to be $1'000mm$, however to save computational time only about $400mm$ of the entire billet length are simulated. The billet preheat is set to $485°C$ whereas the container and the tools are at $495°C$. Finally, three simulations at $3mm/s$ ram speed with and without cooling are conducted.

For the simulation with tool cooling, the cooling channels are positioned as pictured in Figure 3. As it can be seen, the main inlet channel goes through the mandrel and the insert and is divided in five smaller channels with the ration $d_i/d = 0.45$ at the bearing starting location, where the highest temperatures in the insert occur.

For the planned extrusion experiments, liquid nitrogen will be used as a cooling media for the tools. It is important to consider, that the liquid nitrogen undergoes a critical

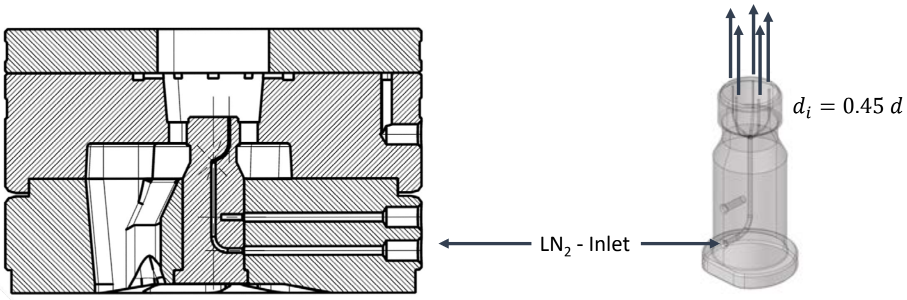
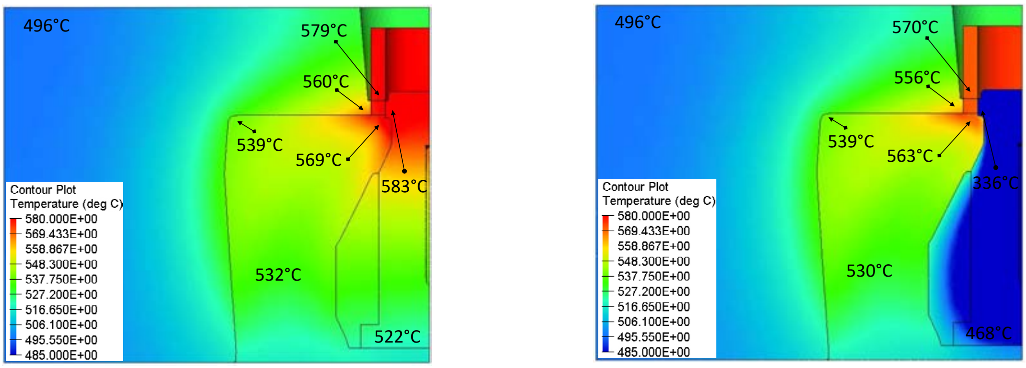


Figure 3: Cooling channel position and geometry for a five-chamber porthole die

phase-change during the cooling process caused by the very high temperature differences between the saturation temperature of the liquid (ca. $-196°C$ at $5bar$) and the wall temperature of the solid (ca. $500°C$). In the case of the extrusion process this temperature change can reach values of about $600°C$, that normally leads to boiling heat transfer characteristics. In the literature for cryogenic machining, several values for the boiling heat transfer coefficient of liquid nitrogen are proposed. However, as mentioned in the work of [8], they change the order of magnitude from $1 \cdot 10^1\ W/m^2K$ [9] up to $1 \cdot 10^4\ W/m^2K$ [10, 11] depending which physical state of the coolant is assumed for the calculations. In the case of aluminum extrusion, most of the studies on liquid nitrogen tool cooling, are based on experimental tests [12, 13, 14] rather than computational temperature prediction. Thus, no knowledge about the possible location of the phase-change or the real physical state of the fluid inside the channels is known. For this reason, while considering the studies on cryogenic machining, two simulations with a heat transfer coefficient of $1'000\ W/m^2K$ and $10'000\ W/m^2K$, assuming cold gas and cold liquid respectively, with a bulk temperature of $-150°C$ are computed.

An exemplary temperature distribution for the tool and workpiece can be found in Figure 4. The extracted temperature values are for the same nodes at the same time-step for the simulation without (left) and with (right) cooling. As it can be seen, the temperatures of the workpiece differ mostly from each other in the profile region. Due to the tool cooling, the heat generated at the bearing location dissipates towards the cooling channels (heat sink), allowing the profile to cool down about $9°C$. A temperature reduction of about $5°C$ is computed instead for the simulation with the surface heat transfer coefficient of $1'000\ W/m^2K$. The average cross-sectional profile exit temperatures are plotted in Figure 5. According to this figure, it can be observed, that the average profile temperature development without tool cooling reaches values above the critical temperature (ca. $560°C$) of the alloy used (AW-6060). Therefore, it can be concluded, that to keep profile quality at the given productivity rate without encountering profile softening, an appropriate tool cooling is necessary. In order to better quantify the cooling capacity and the heat transfer characteristics, a comparison with experimental data will be conducted in a further study. Nevertheless, the potential of nitrogen cooling, more precisely of additively manufactured conformal cooling channels, could be predicted.



(a) No cooling

(b) Heat transfer coefficient $10'000\ W/m^2K$

Figure 4: Temperature distribution for the tool and workpiece at a press stroke of $400mm$

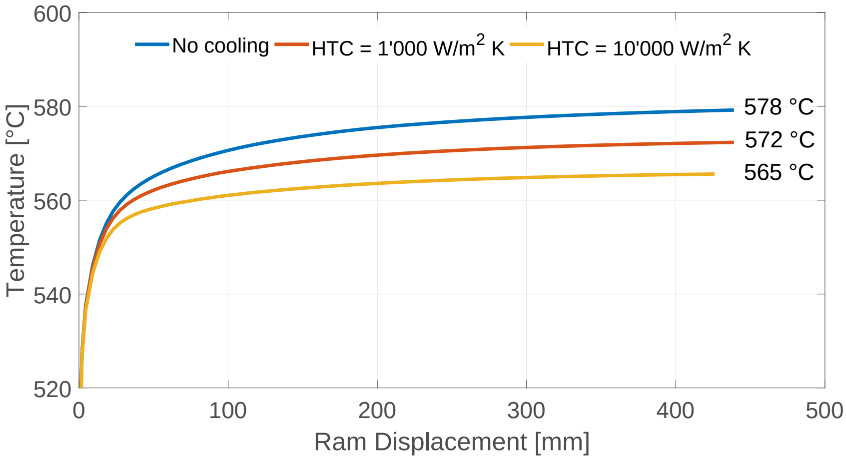


Figure 5: Average profile exit temperature development for the simulations computed with no cooling, $1'000\ W/m^2K$ and $10'000\ W/m^2K$ heat transfer coefficient as a boundary condition

4 EXPERIMENTAL INVESTIGATION OF THE HYBRID SPECIMENS

In Chapter 3, the potentiality of conformal cooling channels has been discussed. The simulations are performed only for the joined tool set-up, because from a computational point of view, under the described model assumptions, the results would not change for the welded tool set-up.

From the manufacturing side however, there are some aspects of the welded tool set-up that need to be addressed. In fact, when using different materials for the additively and the conventionally manufactured parts, the heat treatment strategy plays a relevant role in the manufacturing process of the die-set. Furthermore, the quality of the bonding region between the two welded parts needs to be investigated. Therefore, in this Chapter: the results of tensile tests performed at room temperature on hybrid specimens for different heat treatment strategies will be presented together with micro-graphs of the bonding regions.

Figure 6 shows the four tested versions of hybrid tensile specimens. The conventional part of the tensile bar is either made of hardened or not hardened 1.2343 tool steel. The additively manufactured parts are then selective laser melted out of 1.2709 metal powder directly onto the conventional manufactured round bars. Afterwords, the specimens, three for each variant, are heat treated as follows:

HT1: specimens are hold at 510°C for 8 hours, which is the heat treatment strategy normally used for additively manufactured 1.2709 tool steel

HT2: the other samples undergo a 35 minutes hardening process at $1'020$°C followed by two times tempering for 2 hours at 600°C, which is the heat treatment strategy for (forged) 1.2343 tool steel

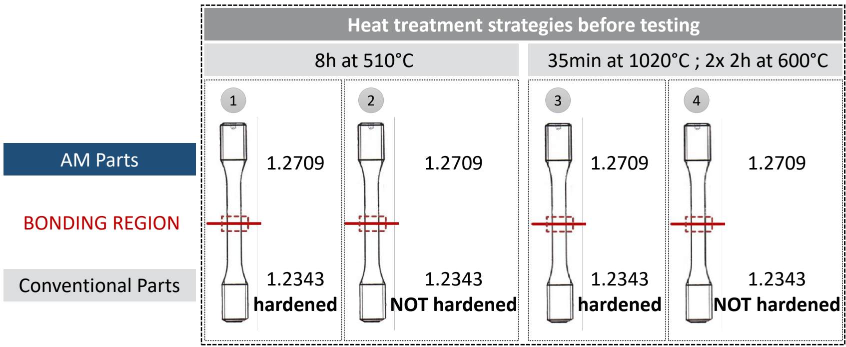


Figure 6: Tested hybrid specimens partially additively (1.2709) and partially conventionally (1.2343) manufactured

In the end, the round bars undergo turning operations to get to the final tensile bar geometry, accordinf to DIN 50125-A, and to remove possible geometry distortions induced by the heat treatment. The results of the tensile tests performed at room temperature are shown in Figure 7. The specimens that were treated based on the first strategy (HT1) show a rather ductile behavior (curves 1 and 2) compared to others (curves 3 and 4). The specimens for curves 1 and 2 show necking at the fracture surface, which lies in the conventional part of specimen made of 1.2343 and not in the selective laser melted part. For the specimens that followed the HT2 strategy, the fracture surfaces lie instead near the bonding region in the selective laser melted part. Figure 8 shows the micro-graphs taken at the bonding region after performing the tensile tests. None of the specimens directly fractured at the bonding layer, hence fulfilling a relevant requirement for the implementation of the welded tool set-up in the industrial framework.

Considering the fact, that the hybrid tool is mainly under tensile loading during the extrusion process, the best results regarding the industrial application are achieved by the

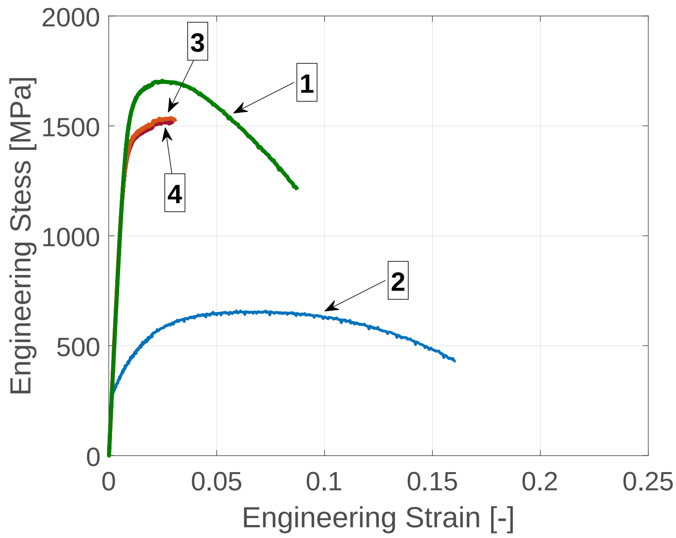


Figure 7: Tensile tests results for hybrid specimens tested at room temperature

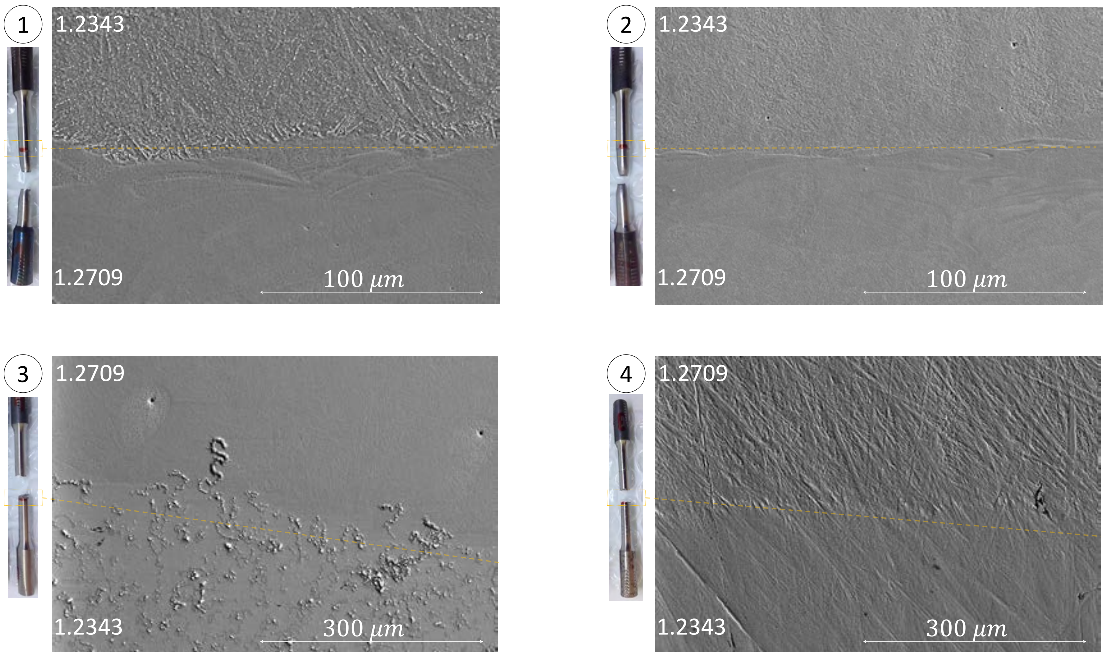


Figure 8: Micro-graphs of the bonding region after tensile testing

manufacturing strategy represented by curve 1 in Figure 7. Thus, for the hybrid tool set-up the conventional parts should be manufactured and hardened as usual. The additively manufactured part should then be directly selective laser melted onto the conventional parts and in the end the entire hybrid tool should undergo the HT1 strategy in order to reach the required hardness of about 55 HRC for the selective laser melted material.

5 CONCLUSIONS

In this study, the use of two hybrid tool set-ups has been discussed. Simulations with and without liquid nitrogen cooling have been presented. These show promising results for the utilization of the hybrid tools in the industrial framework. However, due to the complexity of the tool cooling caused by the inevitable phase-change of the liquid nitrogen, a further study on the heat transfer characteristics coupling extrusion experiments with a numerical analysis should be performed. Material tests for hybrid tensile specimens, for which two different heat treatment strategies were analyzed, are presented and discussed. The specimen following the HT1 strategy and the first manufacturing sequence pictured in Figure 7 show the most promising performance. Moreover, for each specimen micrographs show that failure is not occurring at the bonding region between the two tool steels used for the hybrid tool set-up.

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